Effect of sidereal variation on time-independent probability analysis in long-baseline experiments

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Introduction

Lorentz symmetry is deeply ingrained at the fundamental level in our best theories of nature such as Einstein's general relativity and the Standard Model (SM) of particle physics. Spontaneous violation of Lorentz symmetry can occur in mechanisms of String Theory [1]. This prospect of Lorentz violation leads to the Standard model Extension (SME), which leads to a flurry of experimental searches for the relativity violations. Sidereal variation is one of the major effect allowed by the SME, which occurs due to presence in anisotropic space. It perturbates the neutrino hamiltonian, which directly reflects in the standard oscillation probability. Perturbation in neutrino Hamiltonian produced due to SME can be written as [2]

$$h_{\rm LIV} = 1/E \cdot [(a_L)^{\mu} p_{\mu} - (c_L)^{\mu\nu} p_{\mu} p_{\nu}], \quad (1)$$

where p_μ is the four-momentum, $(a_L)^\mu$ are CPT (charge, parity and time reversal) violating LIV (Lorentz invariant violation) coefficients having dimension of energy, and $(c_L)^{\mu\nu}$ are dimensionless CPT-even LIV coefficients. This LIV perturbation can be further written in the function of sidereal time as

$$(h_{\rm LIV})_{\alpha\beta} = (C)_{\alpha\beta} + (A_s)_{\alpha\beta}\sin(\omega {\rm T}) + (A_c)_{\alpha\beta}\cos(\omega T) + (B_s)_{\alpha\beta}\sin(2\omega {\rm T}) + (B_c)_{\alpha\beta}\cos(2\omega {\rm T}) \quad (2)$$

where ω is the sidereal frequency of Earth, T is the sidereal time at any instant. Amplitudes $(C)_{\alpha\beta}$, $(A_s)_{\alpha\beta}$, $(A_c)_{\alpha\beta}$, $(B_s)_{\alpha\beta}$, and $(B_c)_{\alpha\beta}$ can be defined in terms of LIV coefficients and energy in the Sun-centered frame (follow Ref. [2]). In appropriate experimental conditions, it may be an excellent approximation of expanding oscillation amplitudes in powers of $h_{\rm LIV}$. Up to the leading order, the short-baseline approximation of oscillation probabilities are

$$P_{\nu_\beta \to \nu_\alpha} \simeq \begin{cases} 1 - \sum_{\gamma,\gamma\neq\alpha} P_{\nu_\alpha\to\nu_\gamma}, & \alpha = \beta, \\ |(h_{\rm LIV})_{\alpha\beta}|^2, L^2 & \alpha \neq \beta \end{cases} \quad (3)$$

where the neutrino flavors e, μ, τ are represented by the indices α, β, γ respectively.

Investigation of sidereal variation

The current work has explored LIV as sidereal signal in T2K, NOνA and DUNE experiment's far (FD) detector for some benchmark a_L and c_L parameters. Required initial parameter values are chosen from latest upper limits of different experiments [4].Length and Energy of different experiments which are used for calculations are shown in Table I.

As Eq. 3 is valid only for short-baseline, therefore the analysis of Sidereal variation were performed (previously) for short baseline experiments. However, considering a non-isotropic model, we performed a full three-flavor calculation with GLoBES [3] to see the effect on both the ND as well as FD. As experiments collect data over a long period, neutrinos of different periods face distinct LIV potentials throughout their propagation. This time-dependent modulation introduces LIV parameter interference in Probability (Fig. 1). Fig. 1 exhibits that even a

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non-zero constant value of the LIV parameter $a^X_{\mu\tau}$ generates an uncertainty band (Sidereal time-dependence of perturbation) in the appearance and disappearance channels.

TABLE I: Selected L and E parameters from T2K, NOνA and Dune experiments as required input for the simulation.

	L (km)		Energy range	Peak Energy
	ND	FD	(GeV)	(GeV)
NOνA	1.0	810	0.5-4.0	1.9
T2K	0.225	295	0.1-1.0	0.6
DUNE	0.5	1295	1.0-8.0	2.5

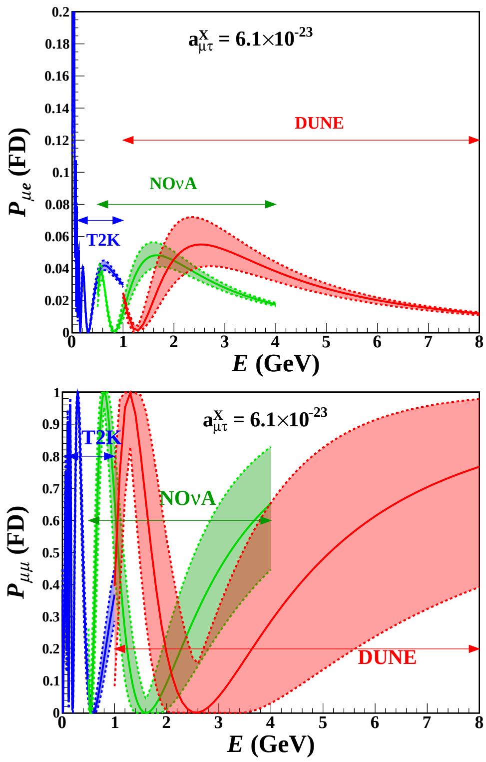

FIG. 1: Uncertainty due to CPT violating LIV parameter $a^X_{\mu\tau}$ in appearance(TOP) and disappearance (BOTTOM) channels in the FD.The solid line represents the standard oscillation probability, and the shaded zone represents the presence of a sidereal dependent non-zero LIV parameter.

In both, appearance and disappearance channels, the sidereal effect is much higher in DUNE than NOνA, and least in T2K. Relative broadening $\equiv (|P^{\mathrm{LIV}_{\max}}_{\alpha\beta}$ - $P^{\mathrm{LIV}_{\min}}_{\alpha\beta}|)/P^{\mathrm{SM}}_{\alpha\beta}$ in probability at their peak energy is calculated and summarized in Table II.

TABLE II: Relative broadening of probability in different channels at peak energy of T2K, NOνA and DUNE experiments.

Experiment	Channel	Peak Energy (GeV)	Broadening
NOνA	$\mu \to e$	1.9	0.27
	$\mu \to \mu$		3.2
	$\mu \to \tau$		0.17
DUNE	$\mu \to e$	2.5	0.56
	$\mu \to \mu$		62
	$\mu \to \tau$		0.22
T2K	$\mu \to e$	0.6	0.16
	$\mu \to \mu$		7.6
	$\mu \to \tau$		0.02

Summary and prospects

A maximum relative broadening is possible in the DUNE FD at the E of interest (see Table II). Thus, a non-isotropic LIV component can affect the oscillation channels in DUNE to a maximum extent. Currently, we are working on the possible effect of this broadening in probability on the sensitivity of standard parameters in the above experiments.

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